Appendix F
Off line Verification Beacon Versus Intersection Beacon Calculations of Minimum Separation Distances

CALCULATIONS OF RE-USE DISTANCES: INTERSECTION (1) TO OFF-LINE VERIFICATION (2)

Beacon Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
General	Center Frequency	Fc	**5.85**	GHz
	Speed of Light	Cf	984251969	feet/sec.
	Wavelength	Lambda	**0.1682482**	feet
	Wavelength in dB	Lambda_dB	**-7.74**	dB feet
	4*PI	F_PI	10.99	dB
Beacon 1 (Intersection)	Height of RSU Antenna	RSU_h	**20.00**	feet
	Height of OBU Antenna	OBU_h	**5.00**	feet
	Maximum Lateral Separation Distance	Sep_max	**50.00**	feet
	Minumum RSU Ant. Angle From Vertical	Ang_min	**30.00**	degrees
	Minimum Lateral Separation Distance	Sep_min	8.66	feet
	Maximum Operating Range	Rmax	52.20	feet
	Maximum Operating Range in dB	Rmax_dB	17.18	dB feet
	Minimum Operating Range	Rmin	17.32	feet
	Minimum Operating Range in dB	Rmin_dB	12.39	dB feet
	Width of Antenna Beam at Longest Range	Wmax	**12.00**	feet
	Antenna Elevation Beamwidth (Horiz. to Ang_min)	RSU_el	60.00	degrees
	Antenna Azimuth Beamwidth	RSU_az	13.11	degrees
	Antenna Gain	RSU_g	16.49	dB
	Maximum Antenna Gain Through Sidelobes	RSU_gsl	1.49	dB
Beacon 2 (Off-Line Ver.)	Maximum Operating Range	Rmax2	**30.00**	feet
	Maximum Operating Range in dB	Rmax2_dB	14.77	dB feet
	Minimum Operating Range	Rmin2	**6.00**	feet
	Minimum Operating Range in dB	Rmin2_dB	7.78	dB feet
	Antenna Elevation Beamwidth	RSU2_el	**20.00**	degrees
	Antenna Azimuth Beamwidth	RSU2_az	**20.00**	degrees
	Antenna Gain	RSU2_g	19.43	dB
	Maximum Antenna Gain Through Sidelobes	RSU2_gsl	4.43	dB
RSU General	Antenna Radiation Pattern Loss	RSU_gl	**3.00**	dB
	Minimum Loss Through Antenna Sidelobes	RSU_sl	**15.00**	dB
	Minimum Received Signal Level (at receiver)	RSU_mrsl	**-94.00**	dBm
	Maximum Interference Signal Level	RSU_int	**-114.00**	dBm
	Isolation Tone to Lower Uplink Band	RSU_TL	**60.00**	dB
	Isolation Tone to Upper Uplink Band	RSU_TU	**60.00**	dB
	Isolation Tone to Adjacent Channel	RSU_TA	**80.00**	dB
	Class A: Isolation Modulated to Lower Uplink	RSU_AML	**40.00**	dB
	Class A: Isolation Modulated to Upper Uplink	RSU_AMU	**60.00**	dB
	Class A: Isolation Modulated to Adjacent Channel	RSU_AMA	**63.00**	dB
	Class B: Isolation Modulated to Lower Uplink	RSU_BML	**50.00**	dB
	Class B: Isolation Modulated to Upper Uplink	RSU_BMU	**60.00**	dB
	Class B: Isolation Modulated to Adjacent Channel	RSU_BMA	**70.00**	dB
	Class C: Isolation Modulated to Lower Uplink	RSU_CML	**60.00**	dB
	Class C: Isolation Modulated to Upper Uplink	RSU_CMU	**60.00**	dB
	Class C: Isolation Modulated to Adjacent Channel	RSU_CMA	**80.00**	dB

CALCULATIONS OF RE-USE DISTANCES: INTERSECTION (1) TO OFF-LINE VERIFICATION (2) (CONTINUED)

OBU Operating Parameters

LOCATION	PARAMETER	LABEL	VALUE	UNITS
OBU	Antenna Gain (35 degrees off boresight)	OBU_g	**4.00**	dB
	Mimimum Received Signal Level (0 dB ant.)	OBU_min	**-40.00**	dBm
	Maximum Received Signal Level (0 dB ant.)	OBU_max	**-14.00**	dBm
	Maximum Interference Signal Level (0 dB ant.)	OBU_int	**-60.00**	dBm
	Maximum Transmit EIRP	OBU_Pmax	**-24.00**	dBm
	Windscreen Loss, One-Way	L_w	**3.00**	dB
	Modulation Loss	L_m	**3.00**	dB
	Realization Margin	L_r	**4.00**	dB
	RF Amplifier Gain	OBU_rf	**10.00**	dB
	Minimum Conversion Gain	OBU_Gain	5.00	dB
	Adjacent Channel Isolation	OBU_AI	**18.00**	dB

Beacon 1 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt_d	18.33	dBm
	Transmit Power for Successful Uplink	Pt_u	17.65	dBm
	Transmit Power for Up and Down Link	Pt	18.33	dBm
	Transmit EIRP	RSU_EIRP	34.82	dBm
OBU	Max. Received Signal Level (0 dB ant.)	OBU_Rmax	-27.42	dBm

Beacon 2 Required Transmit Power Calculations

LOCATION	PARAMETER	LABEL	VALUE	UNITS
RSU	Transmit Power for Successful Downlink	Pt2_d	10.58	dBm
	Transmit Power for Successful Uplink	Pt2_u	2.15	dBm
	Transmit Power for Up and Down Link	Pt2	10.58	dBm
	Transmit EIRP	RSU2_EIRP	30.01	dBm
OBU	Max. Received Signal Level (0 dB ant.)	BU2_Rma	-23.02	dBm

CALCULATIONS OF RE-USE DISTANCES: INTERSECTION (1) TO OFF-LINE VERIFICATION (2) (CONTINUED)

Uplink on Uplink Separation Distance OBU to RSU Antennas

RSU ANT.	SCENARIO	2 on 1	1 on 2	UNITS
Main 1	Same Channel	2,827.35	705.15	feet
Side 2	Adjacent Channel	355.94	88.77	feet
	Adjacent Channel - Off-Line Distance = 10 Feet	N/A	9.96	feet

Downlink on Uplink Separation Distance RSU to RSU Antennas

RSU ANT.	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe of	Tone to Lower Uplink Band	252.21	615.50	feet
Off-Line Ver.	Tone to Upper Uplink Band	252.21	615.50	feet
Beacon	Tone to Adjacent Channel	25.22	61.55	feet
(2)	Class A: Modulated to Lower Uplink Band	2,522.09	6,154.99	feet
	Class A: Modulated to Upper Uplink Band	252.21	615.50	feet
Mainlobe of	Class A: Modulated to Adjacent Channel	178.55	435.74	feet
Intersection	Class B: Modulated to Lower Uplink Band	797.55	1,946.38	feet
Beacon	Class B: Modulated to Upper Uplink Band	252.21	615.50	feet
(1)	Class B: Modulated to Adjacent Channel	79.76	194.64	feet
	Class C: Modulated to Lower Uplink Band	252.21	615.50	feet
	Class C: Modulated to Upper Uplink Band	252.21	615.50	feet
	Class C: Modulated to Adjacent Channel	25.22	61.55	feet
	Class C: Adj. Channel - Off-Line Distance = 10 Ft.	N/A	6.91	feet

Downlink on Downlink Separation Distance RSU to OBU Antennas

RSU ANT.	SCENARIO	2 on 1	1 on 2	UNITS
Sidelobe of	Same Channel	75.36	737.37	feet
ff-Line Ver. (2	Tone - Adjacent Channel	0.01	0.07	feet
	Class A: Modulated - Adjacent Channel	0.05	0.52	feet
Mainlobe of	Class B: Modulated - Adjacent Channel	0.02	0.23	feet
Intersection (1)	Class C: Modulated - Adjacent Channel	0.01	0.07	feet

Uplink on Downlink Separation Distance OBU to OBU Antennas

RSU ANT.	SCENARIO	2 on 1	1 on 2	UNITS
N/A	Same Channel	0.84	0.84	feet
	Adjacent Channel	0.11	0.11	feet

This Page Intentionally Left Blank

Appendix E: Environmental Analysis Framework and Methodology

1.0 Introduction

GTRI is supporting ARINC under Tasks D & E of the ATIS Communications Alternatives Test and Evaluation contract from the Federal Highway Administration (FHWA). The objective of GTRI's effort is to analyze Vehicle to Roadside Communications (DSRC) technologies to determine their applicability to the Intelligent Transportation Systems (ITS) architecture. This analysis is geared toward the refinement of the assessments of the technology for use in ITS.

This report summarizes a framework and methodology for the environmental analysis of DSRC equipment. The environmental analysis will include the analysis of the effects of the following:

a. Weather Propagation Effects
   (1) Fog
   (2) Rain (mist to deluge)
   (3) Snow
   (4) Dust
   (5) Hail.

b. Electromagnetic Environment Effects
   (1) Other DSRC System Emitters
   (2) Other Non-DSRC Emitters
   (3) Unintentional Emitters

c. Physical Effects
   (1) Blockage/Diffraction
   (2) Multipath

2.0 Methodology for the Environmental Analysis

The framework for the methodology will be presented in the following three sections corresponding to the three areas of analysis: weather propagation effects, electromagnetic environment and physical effects. The purpose of this report is primarily to assemble the tools needed to analyze DSRC system performance including range of operation, reliability, effective data rate (capacity), and protocol. These tools will also be useful in the analysis of the design impacts involved in the migration of the 902-928 MHz devices to the 5.850-5.925 GHz band.

The tools and methods presented in the following sections are a collection designed to cover most of the DSRC systems that will be analyzed. Due to the wide variety of DSRC systems, including beacons and ETTM devices, currently available on the market, the analysis of each device or system will likely be unique.

2.1 Weather Propagation Effects

Weather propagation effects on electromagnetic propagation have been studied extensively, especially in the military domain. The primary source of information for this section of the report is a RF propagation study for network planning performed by GTRI for the U.S. Army. [1]

Weather or atmospheric related effects on propagation are generally modeled as a point specific attenuation in units of dB/km. For short range communications systems such as DSRC, the effects can be accurately approximated by assuming the attenuation is constant over the length of the communications channel. If α_r is the attenuation factor due to atmospheric or weather effects (usually expressed in dB/km), the received signal power in free space is calculated by

$$signal = \left(\frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2 L(\alpha'_r)^R} \right)$$

where

where	P_T	=	transmitter or emitter power (W),
	G_T	=	transmitter antenna gain (linear),
	G_R	=	receiver antenna gain (linear),
	λ	=	wavelength (meters),
	R	=	range (meters),
	L	=	miscellaneous receiver losses, and
	α'_r	=	linear atmospheric attenuation factor
		=	$10^{\alpha_r/10}$.

Atmospheric effects on propagation are generally divided into two categories: attenuation due to gases and attenuation due to hydrometeors (water in liquid or vapor form). Gaseous attenuation is caused by the resonance frequencies of certain gas molecules in the atmosphere. Therefore, their effects are at fairly specific frequencies in the SHF (3 - 30 GHz) and EHF (30 - 100 GHz) bands. The resonance of oxygen molecules creates significant attenuation near 60 GHz and 119 GHz. Water vapor resonance affects frequencies near 22 GHz. Below 10 GHz, the attenuation effects of gases in the atmosphere are less than 0.01 dB/km. [3] Therefore, atmospheric attenuation due to gases in the atmosphere is not considered to have a significant impact on the performance of DSRC operating at 902-928 MHz or near 5.8 GHz.

Hydrometeors include rain, sleet, snow, hail, mist and fog. Of these hydrometeors, rain has the most significant impact on the atmospheric attenuation. The frozen precipitations, including sleet, snow and hail, have a significantly lower attenuation than the equivalent the equivalent rainfall rate due to the lower scattering cross section and lower absorption. Also, even dense fog has a lower attenuation than 10 mm/hr (light) rainfall. Therefore, only rainfall need be considered in the analysis of link performance.

The most commonly used model for determining the specific attenuation or attenuation factor due to rain is of the form:

$$\alpha_r = a(R_r)^b \quad \text{(dB/km)}$$

where R_r is the rain rate in mm/hr, and a and b are functions of temperature, rain drop size, rain drop distribution and frequency. Theoretical values for a and b have been derived by several authors using uniformly random rain drop distributions, raindrops modeled as some shape (such as water spheres), and Mie scattering theory. Tables summarizing the various values of a and b for most of these are available in [2]. Variations due to temperature are very small compared to the variation due to frequency or rain rate. Figure 1 shows the attenuation prediction for 10 mm/hr (light) rainfall using the Laws and Parsons low rain rate (LP(L)), Marshall-Palmer (MP), Joss "drizzle" (J-D), and International Radio Consultative Committee (CCIR) models. Figure 2 plots the predicted rainfall attenuation for 100 mm/hr (heavy) rainfall using the Laws and Parsons high rain rate (LP(H)), MP, Joss "thunderstorm" (J-T), and CCIR models. These figures show the effects of a variety of the more common rainfall models.

Figure 1: Attenuation Predictions for R=10 mm/hr

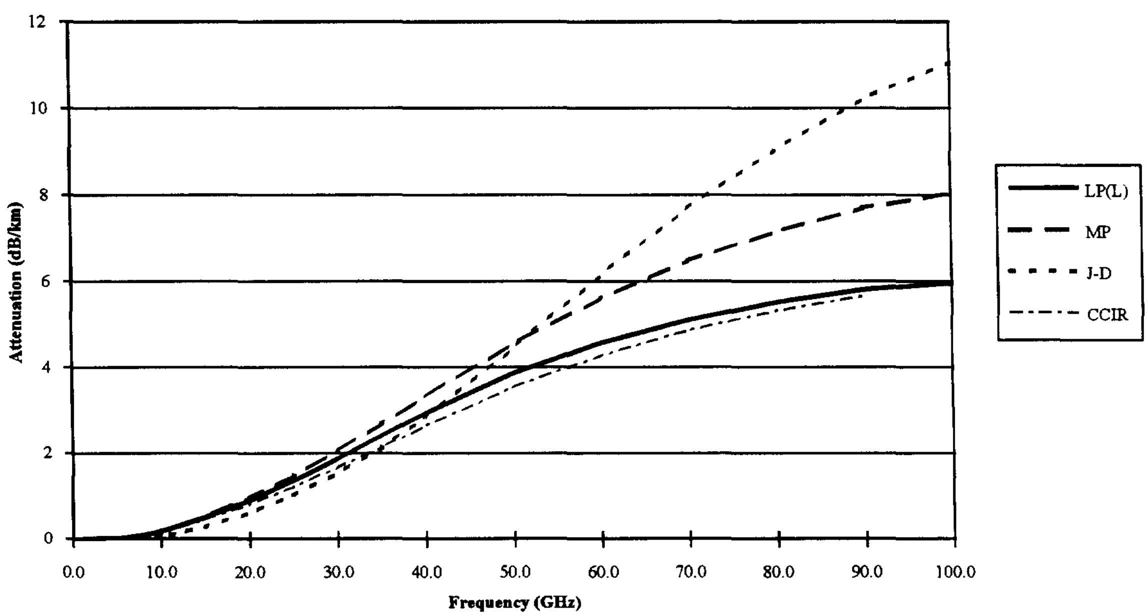
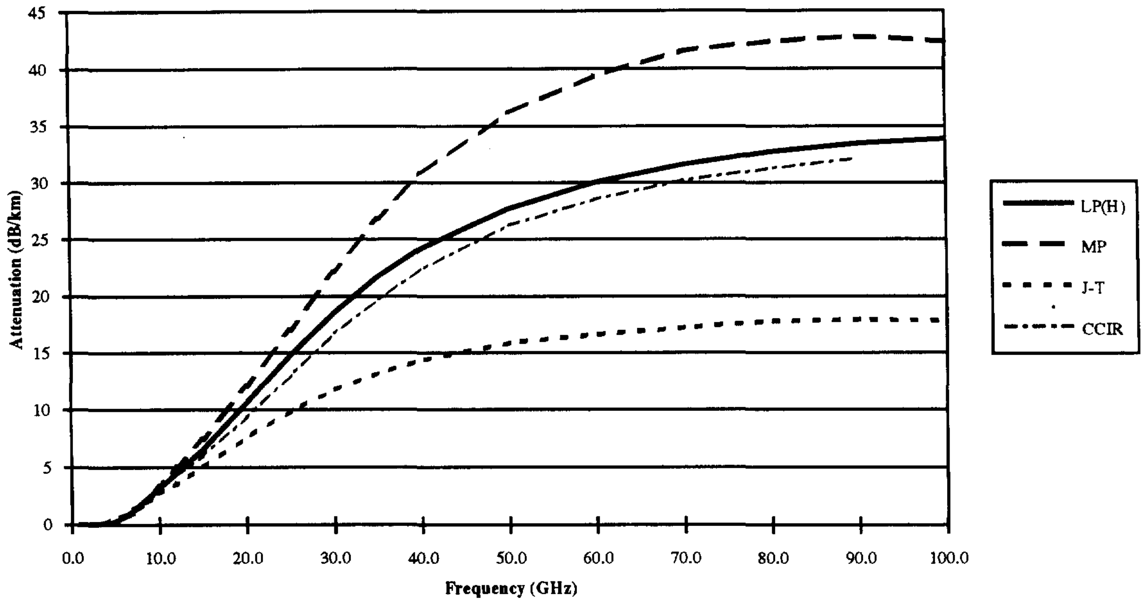


Figure 2: Attenuation Predictions for R=100 mm/hr



Note from Figures 1 and 2 that even at very heavy (100 mm/hr) rainfall rates, the attenuation due to rainfall is less than 1 dB/km for frequencies of 6 GHz or less. Since DSRC systems generally operate over ranges less than or equal to 1 km, then rainfall has no significant impact on the performance of DSRC systems operating at 902-928 MHz or near 5.8 GHz. Consequently, atmospheric effects as a whole have no significant impact on these DSRC systems.

The only remaining weather related or atmospheric effect to consider is the presence of dust or smoke in the atmosphere. The effects of dust and smoke on propagation have been investigated primarily on millimeter wave (MMW) communication systems. Dust has a lesser effect generally than does rainfall, especially at frequencies below MMW. Again, since the DSRC systems generally operate at ranges of 1 km or less, the effects of dust on operation are assumed to be negligible.

Since atmospheric effects are largely negligible at the frequencies of interest here, signal power in free space (or at short ranges) can be calculated by using the following reduced equation for the received signal power (in free space):

$$signal = \left(\frac{P_T G_T G_R \lambda^2}{(4\pi)^2 R^2 L} \right).$$

For operating ranges R much greater than the multiple of the transmitter and receiver antenna heights, the received signal power can be estimated using

$$signal = P_T G_T G_R \left(\frac{h_T h_R}{R^2} \right)^2$$

where h_T and h_R are the transmit and receive antenna heights, respectively. This estimate is based on the assumption of single reflected signal combining with a direct path over a flat surface. It is useful in estimating the average received power in mobile, ground-based communications systems. This method will only be useful in estimating receive power levels for longer range beacon-type DSRC systems. It is not as a rule applicable to shorter range electronic toll collection (ETC) or similar systems which operate at very short ranges.

The equations presented above for calculating receive signal power can be used to estimate a DSRC system's operating range. If the specifications of the system include a minimum receive signal level (MRSL) or minimum signal level (MSL), then this can be substituted for *signal L* in the above equations. The equations can then be solved for the range R in free space using:

$$R = \sqrt{\frac{P_T G_T G_R \lambda^2}{(4\pi)^2 MSL}}$$

If the MSL or MRSL is not provided, then the modulation type, coding and required reliability (i.e. bit error rate) must be considered in order to determine the minimum signal-to-noise ratio (SNR). The SNR can be determined from any of a number of communications books. SNR is equal to the received signal power (*signal*) divided by the received noise power (*noise*). The receive noise power can be calculated from

$$noise = K \cdot T_o \cdot B \cdot NF$$

where	K	=	Boltzmann's constant = 1.38054 * 10^{-23} (W•sec/°K),
	T_o	=	receiver temperature, typically 290 °K,
	B	=	receiver IF bandwidth (Hz), and
	NF	=	receiver noise figure.

Combining the equations for received signal power and receiver noise, using the minimum required SNR (SNR_{min}), and solving for range (assuming free space) results in the following formula for maximum operating range:

$$R = \sqrt{\frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2}{(4\pi)^2 K \cdot T_o \cdot B \cdot NF \cdot SNR_{\min}}}$$

2.2 Electromagnetic Environment Effects

It is difficult to develop a simple methodology for the analysis of the electromagnetic environment effects on DSRC equipment. Many of the effects can only be assessed in specific locations, configurations and surrounding environments. This section will attempt to summarized the primary considerations that must be included in the electromagnetic environment effects analysis. This section is divided into the analysis of the effects of other DSRC system emitters, non-DSRC emitters, and unintentional emitters.

2.2.1 Effects of Other DSRC Emitters

The general effects of other DSRC emitters can be assessed by calculating the interference power received at a particular DSRC receiver. Calculating the interference power at a receiver is similar to calculating the receive power. Adjustments must be made to account for bandwidth mismatch and antenna misdirection (i.e. off-center or sidelobe gain of antennas). The following equation can be used to calculate the interference power received:

$$interference = \left(\frac{P'_T\, G'_T\, G'_R\, \lambda^2}{(4\pi)^2 R^2 L} \right)$$

where P'_T = transmitted power in the bandwidth of the receiver (W),
G'_T = transmit antenna gain in the direction of the receiver, and
G'_R = receiver antenna gain in the direction of the transmitter.

Interference from other DSRC systems must be managed through frequency control, physical separation, antenna directionality and encoding (with or without encryption). Some standards must exist in order to prevent communication disabling interference resulting from two separate DSRC systems operating at the same location and frequency.

Assuming that the disabling interference situation described above is avoided through careful spectrum management or coding, the case of unintentional interference must still be resolved. The most common occurrences of interference will likely be interference between multiple systems located on the same vehicle and co-channel interference within a single DSRC system. Multiple systems on a single vehicle should be avoided if they operate at the same or nearly the same frequencies. That is the goal of standardization and the development of a single system architecture.

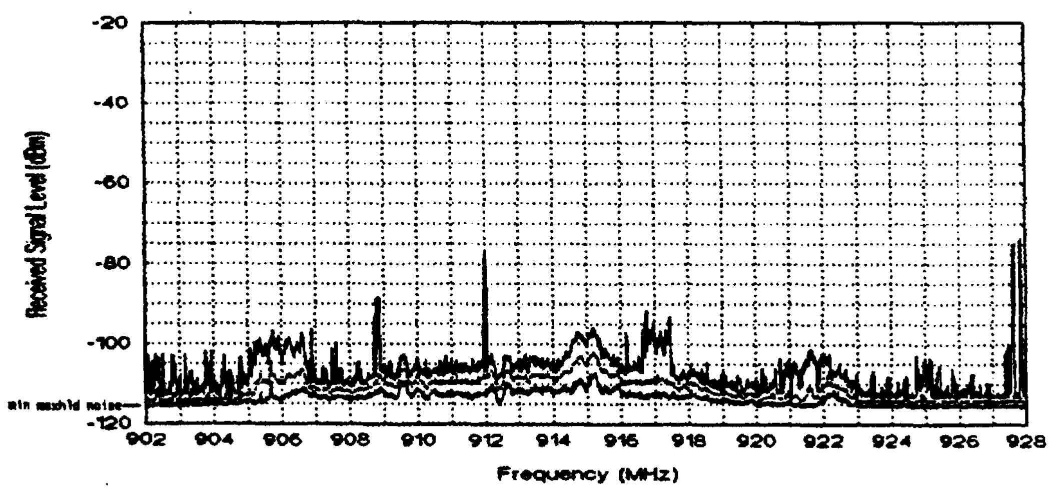
Co-channel interference within a single DSRC system has already been identified as a problem for ETC and commercial vehicle operation (CVO) equipment. Electronic toll tags or CVO transponders in vehicles in adjacent lanes responding to queries intended for a single lane have caused some problems. Typically, the cause is not simply communications through antenna sidelobes, it is often reflections off of the intended vehicle. This problem is not completely solved, though some work is being done with array antennas and shaped beams.

2.2.2 *Non-DSRC Emitters*

DSRC equipment is not the only type of communications equipment in the 902-928 MHz or the 5.8 GHz bands. The 902-928 MHz band is allocated for military radiolocation systems (radars), industrial scientific and medical (ISM), automatic vehicle monitoring (AVM), spread spectrum devices, microwave ovens, digital communications and repeaters. [3] The 5.725 - 5.8750 GHz band is allocated to radiolocation (military radios), ISM (5.800 GHz ± 75 MHz) and amateur (Part 15 - spread spectrum, unlicensed, etc.) systems. [4] Many of the DSRC systems in either of these bands are designed to operate under Part 15 (unlicensed) of the FCC code. Thus they are not protected from interference from either the radiolocation systems or the ISM systems in the bands.

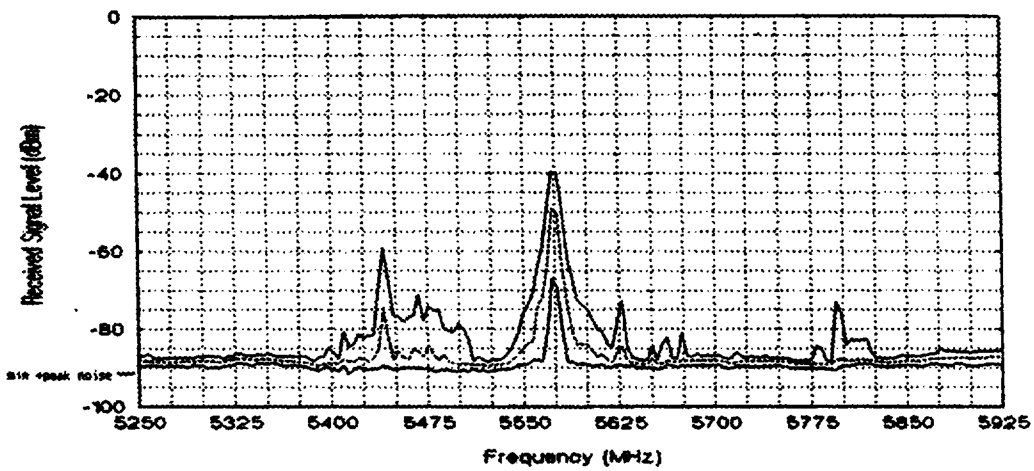
Measurements made in the Denver, Colorado area [3] show that in the absence of military radars, the general background interference is fairly low. Using a 6.1 dB gain antenna with a 45° polarization, the received signal levels in the 902-928 MHz band were usually below -90 dBm (10 kHz bandwidth). There were a few strong signals detected in this band as shown in Figure 3.

Figure 3. NTIA Spectrum Survey Graph Summarizing 23,400 sweep across the 902-928 MHz range (10 kHz bandwidth) at Denver, Colorado [3]



Measurements made at 5.250-5.925 GHz also in the Denver area are summarized in Figure 4. These measurements were taken in several scans using an omnidirectional antenna with a gain of 3.1 dB and show a received signal level of about -82 dBm at 5.8 GHz. All of the prominent signals in the band were the result of radar systems.

Figure 4. NTIA Spectrum Survey Graph Summarizing 26 Scans Across the 5.250-5.925 GHz range (3 MHz bandwidth) at Denver, Colorado [3]



While the measurements made in Denver cannot be applied to all locations or even at all times in Denver, they do represent a typical background signal levels for the 902-928 MHz and 5.8 GHz bands.

Comparing the MRSL of a system to the background noise depicted in Figures 3 and 4 can provide more information on the operating range of the DSRC emitters. The interference power levels received by a DSRC system can be calculated from the signal levels in the Denver measurements by compensating for bandwidth. The received interference power (in dBm) is calculated by

$$received\_interference = P_m + B_R - B_m$$

where

where	P_m	=	power measured at Denver (in dBm),
	B_R	=	10 log(bandwidth of the DSRC receiver), and
	B_m	=	10 log(bandwidth used in the Denver measurements).

The minimum power level at the receiver needed to overcome the interference sources can be calculated by adding the received interference power level to the SNR required at the receiver. If this sum is greater than the MRSL quoted for the system, then the minimum received power level calculated here must be used in place of MRSL in the calculations of maximum operating range discussed in the Weather Propagation Effects section above. Note that this result can only be used as an estimate of the actual system's performance. A spectral site survey is required to identify the background noise and potential interference sources at any specific location.

Special Note: The 5.795-5.805 GHz band is of interest in this current analysis, but of emerging interest is the 5.850-5.925 GHz band for ITS DSRC applications. The latter band is allotted for Government radiolocation and fixed earth-to-space satellite transmissions. ISM emitters are not allowed in this band. Efforts are currently under way to have ITS DSRC systems allotted on a co-primary basis in this band with the satellite earth stations. This would provide the DSRC systems a significant measure of protection from interference from Part 15 (unlicensed) emitters. Also, the satellite ground station emissions are very compatible with the short range DSRC systems and would not likely cause significant interference problems between the two.

2.2.3 Unintentional Emitters

Unintentional emitters consist of natural and man-made sources. The most common method for evaluating the effects of unintentional emissions is to characterize the overall background noise levels caused by these emitters. In Figure 5, the noise levels resulting from the more common unintentional emitters are characterized. The noise levels are given in terms of the antenna noise figure, F_a, due to the external noise. The RMS field strength for a particular bandwidth receiver can be calculated by

$$E_n = F_a + 20\log(f_{MHz}) + B - 95.5$$

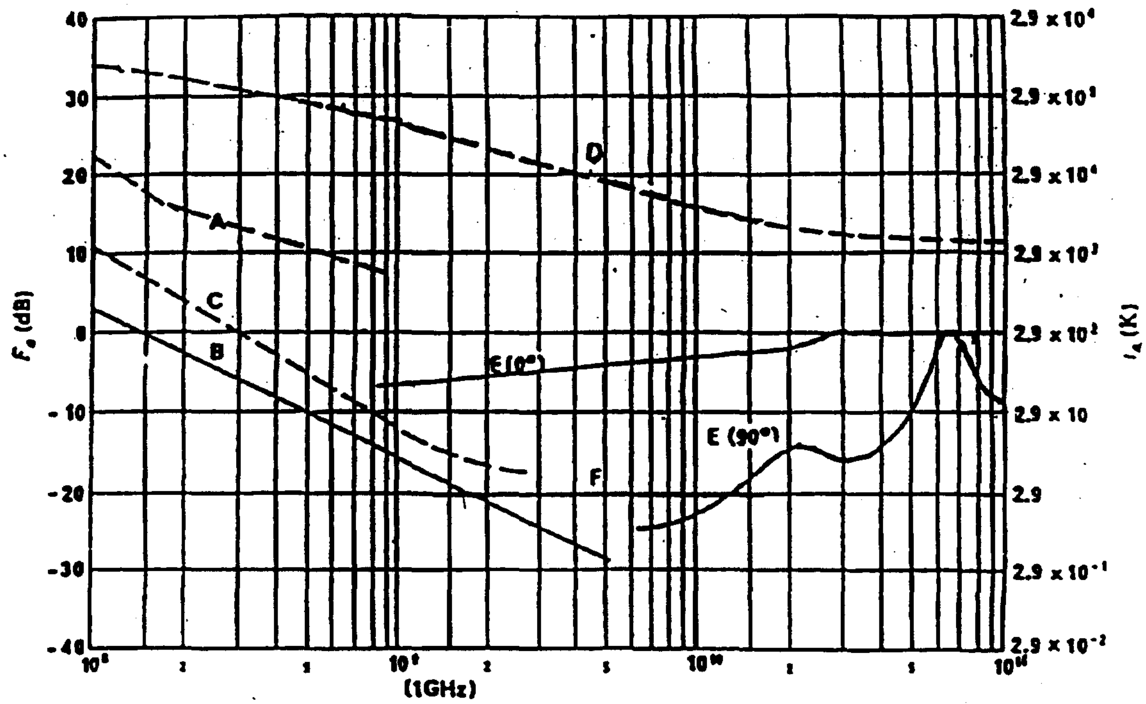
where E_n = $20\log(e_n)$ (dB(μV/m)),
e_n = RMS field strength (μV/m),
f_{MHz} = center frequency in MHz,
B = $10\log(b)$, and
b = receiver bandwidth (MHz).

The received power due to the noise, P_n, can be calculated from the field strength using

$$P_n = 10\log\left[\frac{\left(e_n \cdot 10^{-6}\right)^2}{377} \cdot \frac{G \cdot \lambda^2}{4\pi}\right] - 30 \quad \text{(dBm)}$$

where G = receiver antenna gain (linear). [3]

Figure 5. F_a versus Frequency (100 MHz to 100 GHz) [3]



A. Estimated median business area man-made noise

B. Galactic noise

C. Galactic noise (toward galactic center with infinitely narrow beamwidth)

D. Quiet sun (1/2 degree beamwidth directed at sun)

E. Sky noise due to oxygen and water vapor (very narrow beam antenna; upper curve 0° elevation angle, lower curve, 90° elevation angle

F. Cosmic background, 2.7K

Figure 5 characterizes the noise levels due to galactic noise, sky noise, quiet sun, cosmic background and estimated median business area man-made noise. The highest noise levels are measured with a 1/2 degree beamwidth antenna directed at a quiet sun. Since DSRC systems will likely never direct a narrowband antenna toward the sun, this noise is of little consequence.

The next highest source of noise is the median business area man-made noise. Measurements indicate that this noise is almost entirely due to automotive ignition noise. The measurements that derived this curve in Figure 5 were taken in the mid 1970's and other sources [4] have shown that the automotive ignition noise level is now substantially lower, about 5 dB at the frequencies of interest here. [4] Given that these results are general background noise levels and may not consider the noise level on the roadway itself, it is probably safer to use the levels in Figure 5 when estimating noise due to automotive ignition and its effects on DSRC systems.

The only natural source of noise or interference which is not shown in Figure 5 is lightning. Lightning produces significant interference at frequencies below 100 MHz, but is not significant at the frequencies considered for DSRC in this analysis, especially at 5.8 GHz. [5] Therefore, further analysis of interference due to lightning is not considered in this report.

The effect of the unintentional emitters on the performance of the DSRC system performance is straight-forward analysis. If the noise power from the unintentional emitters (man-made or natural) is significantly higher than receiver noise power (see Section 2.1) and the interference power due to other DSRC and non-DSRC emitters (see Sections 2.2.1 and 2.2.2), then use the power level for the unintentional emitters in determining the maximum operating range of the DSRC system under study.

2.3 Physical Effects

In this section, an overview of the effects of blockage/diffraction and multipath will be considered. General theory for evaluating the effects of these physical situations on the performance of DSRC systems will be presented. The specific method and calculations required to perform the analysis of diffraction and multipath can use the results presented in this section. However, the precise methodology for assessing the performance of the DSRC systems is highly dependent on the physical implementation of the system.

2.3.1 Diffraction Calculations

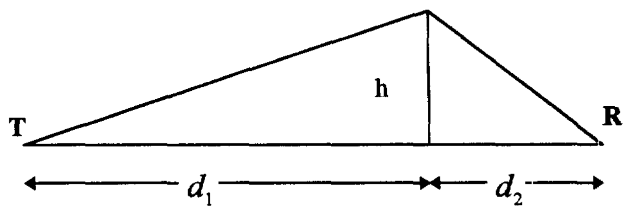
2.3.1.1 Introduction

This section serves three functions. It summarizes the correct analytical formulations required to do knife-edge diffraction loss, it provides a simplified means of doing those calculations, and it then summarizes how knife-edge diffraction can be taken account of in some simple, baseline vehicle-beacon scenarios. Knife edge diffraction can then be used to estimate diffraction around objects which block the line of sight between the DSRC transceivers.

2.3.1.2 Results from Classical Diffraction Theory

In the developments of this section, the parameter v, a kind of height parameter normalized to wavelength, plays an important role. This parameter is expressed in terms of the parameters defined in Figure 6. Any actual diffraction problem geometry must be

Figure 6. Diffraction geometry



mapped onto this geometry. What appears here as the linear distance between T and R, must be measured along the line of sight, h being the length of the orthogonal projection from the knife-edge diffraction point onto the LOS path.

In terms of the quantity [8]

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}$$

and the Fresnel integrals

$$C(v) = \int_0^v \cos\left(\frac{\pi}{2}t^2\right)dt \qquad \text{and} \qquad S(v) = \int_0^v \sin\left(\frac{\pi}{2}t^2\right)dt$$

the complex ratio of the field that exists due to diffraction to the field that would have existed had there been no knife edge is

$$F(v) = \frac{E}{E_0} = \frac{(1+j)}{2}\left[X(v) - jY(v)\right]$$

where

$$X(v) = \frac{1}{2} - C(v) \qquad \text{and} \qquad Y(v) = \frac{1}{2} - S(v)$$

2.3.1.3 Approximations to Classical Diffraction Theory

It is a simple matter to take the magnitude-squared value of *F(v)*, represent it in decibels, and then take the derivative to obtain

$$\frac{d}{dv}\left[|F(v)|^2\right]_{dB} = \frac{10}{\ln 10}\frac{1}{|F(v)|^2}\frac{d}{dv}\left[|F(v)|^2\right]$$
$$= \frac{20}{\ln 10}\cdot\frac{X(v)X'(v)+Y(v)Y'(v)}{X^2(v)+Y^2(v)}$$

Evaluating this expression at the zero point, we have

$$\left.\frac{d}{dv}\left[|F(v)|^2\right]_{dB}\right|_{v=0} = \frac{-20}{\ln 10} = -8.69 \text{ dB}$$

which immediately gives the linear approximation for the region centered at v=0.

Two approximations were used for simple diffraction loss calculations. The expressions give the signal level in dB according to the following:

$$FdB(v) = \begin{cases} -6-8.69v & |v|<1 \\ 20\log\left(\frac{.225}{v}\right) & v \geq 1 \end{cases}$$

The first of these, as described above, was developed at GTRI for this program. The second is due to Lee [7]. Because of a discontinuity at the point $v = 1$, these curves were spliced together over a region $v_1 \leq v \leq v_2$ containing the $v = 1$ point. Using weighting functions defined according to

$$w_L(v) = 1-\frac{v-v_1}{v-v_2} \quad \text{and} \quad w_R(v) = 1-\frac{v_2-v}{v_2-v_1}$$

and defining the left-hand ($|v| < 1$) and right-hand ($v \geq 1$) expressions

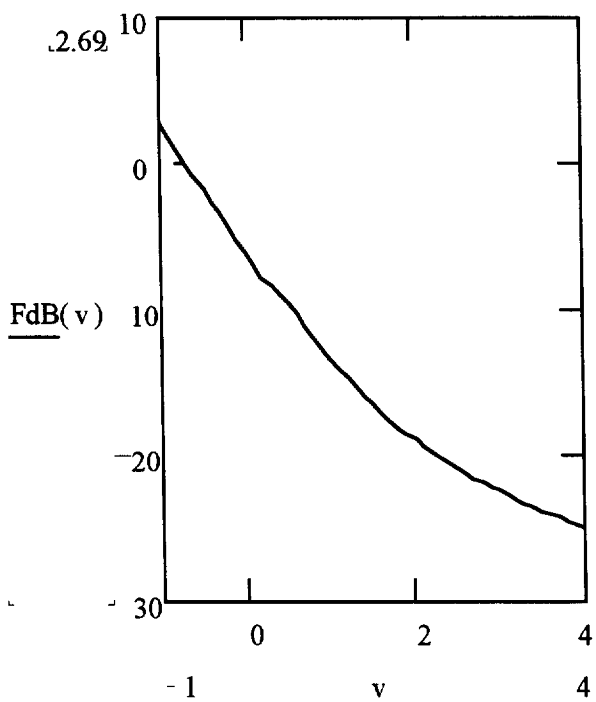
$$FLdB(v) = -6-8.69v \qquad |v|<1$$
$$FRdB(v) = 20\log\left(\frac{.225}{v}\right) \qquad v \geq 1$$

we use

$$FdB(v) = \begin{cases} FLdB(v) & v < v_1 \\ w_L(v)FLdB(v) + w_R(v)FRdB(v) & v_1 \le v \le v_2 \\ FRdB(v) & v > v_2 \end{cases}$$

for the smooth curve expression covering both ranges. The plot resulting from this expression is shown in Figure 7 (using $v_1 = 0.75$ and $v_2 = 1.25$) and aligns very precisely with the classical results that are calculated with much greater labor. [8]

Figure 7. Diffraction loss



2.3.1.4 Sample Calculation

In order to exercise the derived mathematical results and develop some insights into the manner in which results will differ according to the different operating frequencies, we set up a "snapshot" calculation of an electronic toll collection (ETC) scenario. In this scenario, a relatively large truck (18' high) is followed by a much smaller vehicle (receiving antenna 3' off the ground). The car is closely following the truck such that the antenna of the smaller vehicle is 15' behind the truck. The ETC fixed antenna is mounted at a height of 21' and the antenna beam is elevated 60° from downward vertical toward the oncoming traffic. The "snapshot" takes place at just that instant that the trailing top corner of the truck passes through the center of the antenna beam.

The physical situation described above must be mapped onto the geometry used to define the parameters in Figure 6. Although tedious, there are no conceptual challenges to such a mapping and the results are:

$$h = 1.19$$
$$d_1 = 5.88$$
$$d_2 = 21.17$$

The one remaining undefined parameter in the definition of v is the wavelength (frequency). These are:

$$f_1 = 915MHz \quad (\lambda = 1.07 \text{ ft})$$
$$f_2 = 5.8Ghz \quad (\lambda = .17 ft)$$

For each of these, the parameters v_{f1} and v_{f2} follow easily and the corresponding signal levels S_1 and S_2 can easily be calculated from the equations above. Corresponding to the frequencies just given, these values are:

$$S_1 = -11.45\text{dB} \quad \text{and} \quad S_2 = -18.70\text{dB}$$

Therefore, blockage has a significantly greater impact on the received power at the vehicle at 5.8 GHz than at 915 MHz.

2.3.2 Multipath Calculations

Multipath between beacons and vehicles, unless specific efforts are made to avoid it, can be an extremely degrading influence on communications --- and extremely difficult to analyze.

Despite the complexity of multipath phenomena, insights into multipath can be gained by considering some very simple models. It is reasonable, in developing simple guideline equations for calculating the effects of multipath, to ignore the free space loss of the LOS path, which can be calculated separately using simple expressions, and concentrate on the effects of the multipath.

The simplest multipath model of all is the single reflection model. This model consists of two antennas at heights h_1 and h_2, each separated from a ground reflection point by distances d_1 and d_2 respectively. The direct LOS path of distance R between the antennas differs from the length of the reflected path in such a way as to introduce a delay difference $\tau(t)$ between the two paths. In the current application, this delay difference, of course, is generally time-varying due to the motion of the vehicle.

2.3.2.1 Fade Spacing

For the model described above, the deep fade centers occur whenever

$$f \cdot \tau(t) = n \qquad n = 0, \pm 1, \pm 2, \cdots$$

i.e. whenever the delay difference $\tau(t)$ changes by an amount

$$\Delta\tau = \frac{1}{f}$$

From this it follows immediately that for some $f_2 > f_1$, it follows that $\Delta\tau_2$ is smaller than $\Delta\tau_1$ by an amount f_1 / f_2, i.e.

$$\Delta\tau_2 = \frac{f_1}{f_2} \cdot \Delta\tau_1$$

For $f_1 = 915$ MHz and $f_2 = 5.8$ GHz, the ratio is 0.158. The result of this analysis shows that the fades will occur much more frequently for a DSRC system operating at 5.8 GHz than for a similarly configured system operating at 915 MHz. The effects of the decreased fade intervals at 5.8 GHz are dependent on the difference in data rate, modulation and coding between the systems operating at the different frequencies. The actual calculations of the fade interval are highly dependent on the actual configuration of the DSRC system. This analysis presents only a comparison of the fade intervals.

2.3.2.2 Fade Durations

For the simple model given above, the complex representation of the fading on a single tone of frequency *f* is given by

$$s(t) = \left(1 + \alpha(t)e^{-j2\pi f\tau(t)}\right)e^{-j2\pi ft}$$

where $\tau(t)$ is the delay difference and $\alpha(t)$ is the generally time-varying reflection coefficient. For movement of the vehicle through a small localized area it is reasonable to treat the reflection coefficient as if it were constant.

By examining a phasor diagram, drawing a fade circle of radius L and a rotating phasor arm of length α[1], it is possible to determine the fraction of the phasor rotation cycle that the resultant phasor has magnitude less than L. The result is the fraction of time that that fades are below the level L. This formula is given by

$$G(L,\alpha) = \left(\frac{\alpha}{\pi}\right)\cos^{-1}\left\{\frac{1}{2\alpha}\cdot\left[1 + \left(\alpha^2 - L^2\right)\right]\right\}$$

This expression has not yet been plotted or checked other than in a trivial way, and may need to be modified. Note, however, that it does not depend on frequency. To obtain the amount of absolute time that a fading signal spends below a certain level, one must first determine the fade spacing as in the previous section. Fade spacing or interval, definitely dependent on frequency, are equal to the period of the rotation of the phasor. One then

[1] To get non-zero results, this must be done in such a way that $1 - \alpha < L$.

multiplies by the fraction given here, G, to determine the true, absolute duration of time (over one period) that the signal will spend below a certain level.

Note that G can also be used to give a rough estimate of the bit error rate (BER) of the channel due to fading. If it is determined that a fade less than L results in random bit sequences being received, then the average BER due to fading is approximately $0.5/G$. If the DSRC system is using a sufficient interleaver, then the bit errors can be assumed to be randomly occurring (as opposed to burst errors).

Other simple multipath models for specific implementations of DSRC systems have been assessed through computer modeling. One particular paper analyzed an ETC system and demonstrated that the multipath environment differed depending on the type of vehicle passing through the toll collection zone. In this example, the primary multipath reflector for a car was the hood, but for a van with no hood the primary reflector was the road surface. These two vehicles had dramatically different multipath characteristics. [9]

3.0 Conclusions and Overview of the Environmental Analysis Methodology

The exact "methodology" for evaluating a particular DSRC system will ultimately depend on the system configuration and implementation. The methods of evaluation presented in Section 2.0 provide the basic tools for conducting a system-level analysis of the performance of DSRC systems.

Section 2.1 provides the equations necessary to calculate maximum communications range for a given system. In this analysis, only basic propagation is considered. Equations for free space propagation are included. Also provided is an equation for estimating the mean received power for longer range DSRC systems including the basic effect of multipath (not fading). The analysis shows that weather will have very little effect on the performance of DSRC systems operating in either the 902-928 MHz or the 5.8 GHz frequency bands. Therefore, only basic propagation equations need to be considered.

Section 2.2 demonstrates the analysis methods for the consideration of interference. This section provides the formulas for deriving noise or interference power levels. These interference power levels can be used in place of or in connection with the receiver noise level in Section 2.1 to derive the maximum operating range for the DSRC systems.

The analysis of the interference due to other emitters in the frequency band of the DSRC (Section 2.2.1) is conducted using modified free space equations to account for off-boresight antennas and mismatched bandwidths. Surveys of the spectrum around Denver, Colorado are the basis for the analysis of the general effects of non-DSRC emitters (Section 2.2.2). These provide a basic background noise level over the frequency bands of interest.

Unintentional emitters and natural noise sources are considered in Section 2.2.3. It is shown that the primary noise source is automotive ignition noise. Natural noise sources have considerably lower power than the ignition noise. Graphs and equations for estimating the background noise due to automotive ignitions are provided.

Section 2.3 presents the basic equations and theoretical results necessary to assess the effects of diffraction and fading. The diffraction results (Section 2.3.1) can be used to estimate the reduction in signal levels due to antenna blockage for very short range DSRC systems such as those used in electronic toll collection. Longer range blockage results will probably be best assessed using the theoretical Rician fading environment [10].

The multipath environment (Section 2.3.2) is perhaps the most difficult environment to develop a simple methodology for analysis. The multitude of possible DSRC configurations makes defining a single model impossible. Multipath analysis is therefore characterized in this analysis by viewing a 2-ray multipath model. Using this model, an estimate of the fade intervals and the fraction of time in a fade is calculated. These parameters are highly dependent on frequency, physical implementation, and the coefficient of reflection of the surrounding objects (road surface, car hood, buildings, etc.).

This report provides the framework for analyzing primarily the maximum operating ranges of DSRC systems. Some analysis of the effects of multipath are also provided. To assess more detailed parameters such as bit error rate (BER), protocol performance or effective data rate will require analysis very specific to the individual DSRC system. The modulation, coding and link protocols will have to be evaluated. To summarize the methods for analyzing each type of DSRC system to this level of detail is beyond the scope of this report. Several good mobile communications, coding theory and network technical reference books exist which cover these analysis techniques.

The methods of analysis provided in this report will be modified, updated or added to as necessary to perform the analysis of the DSRC systems.

References

[1] Collins, D. J., Howard, D. H., and Harvey, B. A., "RF Propagation Modeling Support For Network Planning Final Technical Report," GTRI Final Report under U.S. Army CECOM contract # DAAB07-93-C-B772, GTRI Project # A-9590, July 25, 1994.

[2] Olsen, Roderic L., D. V. Rogers, and D. B. Hodge, The aR^b Relation in the Calculation of Rain Attenuation, *IEEE Transactions on Antennas and Propagation*, Vol. AP-26, No.2, March 1978, pp. 318-329.

[3] Sanders, F. H., and Lawrence, V. S., "Broadband Spectrum Survey at Denver, Colorado," NTIA Report 95-321, U.S. Department of Commerce, September 1995.

[4] "Intelligent Vehicle Highway System Spectrum Support Outline for the 5725 - 5850 MHz Band," Draft NTIA Report, October 1995.

[5] Spaulding, A. D., "Technical Evaluation of the 2.45 and 5.8 GHz ISM Bands for Intelligent Vehicle Highway Systems."

[6] Shumpert, T. H., Hannell, M. A., and Lott, G. K., "Measured Spectral Amplitude of Lightning Sferics in the HF, VHF, and UHF bands," *IEEE Transactions of Electromagnetic Compatibility*, Vol. EMC-24, pp. 368-369, August 1982.

[7] Lee, W.C.Y., *Mobile Communications Engineering*, McGraw-Hill, New York, 1982.

[8] Parsons J.D., *The Mobile Radio Channel,* John Wiley & Sons, New York, 1992, pg. 37-43.

[9] Wietfeld, C., and Rokitansky, C., "Performance of Vehicle-Roadside Communication Systems supporting Multiple RTI-Applications," *1994 Vehicular Navigation & Information Systems Conference Proceedings.*

[10] Jakes, W. C., editor, *Microwave Mobile Communications*, IEEE Press, Piscataway, New Jersey, 1974.